Climate change impacts on renewable electricity generation

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Abstract

Generation of renewable energy is strongly related to climate, and could be vulnerable as the climate changes in the coming decades. The assessment of the potential risks is a new and evolving area of science. In light of the rapid pace of development and more prominent contribution of renewables to UK electricity generation, this work presents a summary of the current state of knowledge in the field, and highlights some of the critical parameters and areas of uncertainty. An assessment of potential changes in the levelised cost of energy is presented, with the caveat that this is entirely based on existing data, which in some cases is highly uncertain. The areas of critical research for both understanding climate, and engineering for adaptation are discussed.

Keywords chosen from ICE Publishing list

Energy, infrastructure, weather

List of notation

DECC	Department of Energy and Climate Change
GHG	Greenhouse gas
HadRM3	Hadley Centre Regional Climate Model 3
LCOE	Levelised cost of energy
NAO	North Atlantic Oscillation
PV	Photo-voltaic
UK	United Kingdom
UKCIP02	United Kingdom Climate Impacts Programme 2002
UKCP09	United Kingdom Climate Impacts Programme 2009
WEC	Wave energy converter

1. Introduction

An increasing amount of renewable generation is being connected to the UK electricity network in order to address both emission reduction targets in an attempt to mitigate climate change, and energy security needs as traditional fossil fuel reserves become depleted. Many sources of renewable electricity are sensitive to increases and decreases in the mean and variability of a range of climatic parameters, and are thus vulnerable to climate change. Wind power is, obviously, sensitive to changes in wind speed. Other major sources of renewable electricity include hydropower, which depends on a balance of rainfall and evapo-transpiration (a function of temperature and humidity, among other things), and solar power, which relies on incoming radiation.

Many of these climatic factors are projected by the current generation of climate models to change under future greenhouse gas (GHG) emission scenarios, giving rise to additional uncertainty in the future potential energy production from renewable sources. Any change in production will have consequences for the cost of energy and thus the risk must be carefully considered. Alongside the resources, changes to other parameters that may affect infrastructure in general such as extreme wind speeds or flooding, could have a major impact on renewable electricity generation. This, again, would have operational, financial and wider economic impacts for the energy system.

2. Potential impacts of climate change

2.1 Renewable electricity generation mix in the UK

Figure 1 shows the contribution of each type of generation to the total electricity produced from renewable sources in 2014 (DECC 2015) . Hydropower, which contributed 9% of the total, is considered to be a mature technology, having been deployed on a large scale in the post-war era, mainly in Scotland. More recent developments tend to be smaller, ‘run of river’ schemes, but are still concentrated in mountainous regions of Scotland.

Onshore wind turbines are relatively mature, and were responsible for 29% of electricity from renewables in 2014. . Offshore wind has gained momentum in the last 4-5 years, and contributed 21% of the renewable generation in 2014. The distribution of installed wind power capacity around the UK can be seen in Figure 2, created using data from (DECC 2014b). In total, on- and offshore wind produced around half of all renewable electricity in 2014.

Solar power, despite being a fairly mainstream technology in other parts of northern Europe, particularly Germany, has until recently been relatively uncommon in the UK. The high capital cost of photo-voltaic (PV) panels, the large areas that they require, and the anecdotal belief that the UK is ‘not sunny enough’, perhaps contribute to this. Wave and tidal power produced a tiny fraction of the renewable electricity generation in 2014 although these technologies are still in development, with most of the power generated being the result of testing brand-new devices.

Bio-energy comes from a number of different sources. In 2014, it contributed 35% of the total renewable generation, and of this, around a fifth was landfill gas and three fifths plant biomass, and the remainder made up of smaller contributors.

In total, renewables produced 19.2% of the total electricity generated in 2014 (DECC 2015), increasing from under 3% in 2000 (DECC 2014a). The Climate Change Act 2008 requires that the GHG emissions in 2050 be '*at least 80% lower than the 1990 baseline*' (Anon n.d.). and thus to meet this target, the share of renewable energy would be expected to increase further in the coming decades. National Grid have developed a set of 'pathway' electricity generation scenarios representing possible generation mixes up to the 2030s in order to model future demand and network requirements (National Grid 2014). In the 'slow progression' and 'gone green' scenarios, for example, the proportion of electricity generated by renewables would be expected to increase from existing levels to 55-60%, with wind contributing 40% of the total generation output, and the remaining 15-20% assigned to the combined total of bioenergy, hydro, marine and solar PV, The 'no progression' and 'low carbon life' scenarios have renewables contributing 30-40% of the total electricity generation, with wind again the main player in both at between 19 and 26% of the total. In either case, the contribution of wind power, in particular, to the national electricity supply is expected to increase most significantly. Even under the lowest scenario assumption, wind power would be expected to double its installed capacity by 2035, and to more than quadruple under the highest scenario assumption.

2.2 Climate impacts on renewable resources

Many of the renewable technologies are inherently dependent on climate factors; that is, their power output is directly related to a specific climate variable. The bio-energy technologies are slightly different, as they often have some climate dependencies but do not necessarily have such a direct relationship. Bearing this in mind, each technology will be discussed separately in this section.

2.2.1 Wind power

The power density available from the wind (P, W/m^2) is a function of the wind speed (U, m/s), such that:

$$P = \frac{1}{2}\rho U^3$$

where ρ is air density (kg/m^3) (Manwell et al. 2002). This cubic relationship suggests that small changes in wind speed could have a proportionately larger impact on wind power availability. The expected power produced by a turbine at a given incoming wind speed can be calculated using a 'power curve'. A typical power curve for a Vestas V90 3MW wind turbine is shown in (Vestas Wind Systems A/S. 2004), indicating that, for example, the turbine will start producing power at wind speeds around 3 m/s, reaching full rated power at 15 m/s. The turbine will cut out at speeds greater than 25 m/s to prevent damage to the turbine.

Some typical distributions representing the proportion of time that the wind is blowing at a given speed are shown with their representative Weibull shape and scale parameters in Figure 3. The scale parameter is related to the mean wind speed – a higher mean will lead to a larger scale parameter. The shape parameter is related to the variability of the wind speeds around the mean, with a distribution having a lower shape parameter showing greater variability. A change in the characteristic distribution will lead to a different sum total of energy generated over a given period of time. For example, if the 'tail' of the distribution extends to the right, more extreme wind speeds within the 'cut-out' region of the wind turbine might be expected. Variability at a short time scale is typically the most problematic aspect of wind power, and increasing variability could be more difficult to manage. Conversely, a reduction in variation would probably be considered beneficial. The seasonal variations currently follow consumer demand – i.e. lower output in summer and higher in winter. The consequences of a change in the seasonal pattern would be judged in the context of any concurrent changes in demand patterns. For instance, an increase in output in winter would be advantageous if electric heating were to become more prevalent, whilst a decrease in summer output would be detrimental if air conditioning were more commonly used.

Considering mainly mean and variability, extensive work to examine the changes in wind climate projected by climate models has been carried out looking at the Baltic Sea area (Pryor, Barthelmie, et al. 2005; Pryor, Schoof, et al. 2005). There are some indications of a potential strengthening in winter wind speeds, but a key message is that the results are considered to be highly uncertain. In a later review of climate change impacts on wind energy (Pryor & Barthelmie 2010), the same authors conclude that on the basis of the evidence, the future changes projected with current models are unlikely to have a discernible effect on wind power generation.

Looking specifically at the UK, two studies (Harrison et al. 2008; Cradden et al. 2012), using independent models found some evidence of a strengthening seasonal wind speed pattern – increases in winter, decreases in summer – that could lead to impacts on the expected power output in these seasons. The authors again had concerns regarding the high degree of uncertainty in the results.

From day-to-day, spatial distributions of wind speeds around the UK depend on the weather systems affecting the country. The dominant patterns are driven by a storm track bringing in areas of low pressure from the Atlantic, which follow broadly similar paths across the country. This leads to higher average wind speeds in northerly and westerly areas. There is some evidence to suggest that the paths may change under future climate change scenarios – 'a shift in the storm track' (Jiang & Perrie 2007). In such a scenario, the expected generation from the existing wind farm configuration could change, possibly leading to a different evolution of optimal wind turbine sites.

2.2.2 Hydropower

Hydropower exploits the potential energy of water falling over a vertical height (or head) with the available power, *P* (W), given by:

$$P = \rho g H Q$$

where ρ is water density (kg/m^3), *g* is gravitational acceleration (9.81 m/s^2), *H* is the head (m) and *Q* is the flow rate (m^3/s). Power production is determined by river flow rates which vary substantially within the year and year-to-year. Smaller catchments, particularly in mountainous areas, may experience variability on much shorter time scales.

The design of hydro schemes relies on a form of cumulative probability distribution: the flow duration curve. The production is limited by maximum (rated) and minimum flows through the turbines together with specified flow rates that bypass the scheme (compensation flow, typically the 90th or 95th percentile). Figure 4 gives an example of a flow duration curve showing a hypothetical potential change between current and future flow regimes. The shaded areas indicate the gross energy potential which changes with the flow patterns.

The flow in the river at any instant is determined by the catchment area as well as the water balance: a function of precipitation, evapotranspiration and any water entering or leaving long term storage. Changes in the volume and timing of precipitation will therefore alter river flows. The literature highlights a tendency for catchments to 'amplify' changes in precipitation with substantially greater changes in river flow (Mukheibir 2013). In part this relates to the non-linear relationship between soil moisture and runoff and the amplification effect is more apparent in catchments with the lowest proportion of rainfall going to runoff, typically the most arid. The composition of precipitation (for example, rain or snow) also has a substantial impact, with snow cover playing a major role in regulating winter and spring flows. Potential evapotranspiration is a complex function of temperature, radiation, humidity, wind speed and other variables. In a warmer climate the rate of evaporation will increase along with the ability of the atmosphere to hold the water. Actual evapotranspiration depends not only on the potential but also the availability of moisture in soils and water bodies.

Hydropower has been extensively assessed for climate vulnerabilities, due to its major global contribution to energy. Much of the literature is for overseas locations with large hydropower facilities and relative importance for energy supply, particularly North America (e.g.,Weyman & Bruneau 1991; Minville et al. 2010) and Africa (e.g., Riebsame W E et al. 1995; Harrison & Whittington 2002). A key finding of many of these studies is that the sensitivity of hydropower production to changes in climate increases significantly as the amount of reservoir storage declines. In the UK as a whole, hydro now has a more modest role hence few studies exist in contrast to substantial amounts of climate impact studies focussed purely on hydrology (e.g. Fowler & Kilsby 2007), water resource systems (Fowler et al. 2007) and reservoir safety (Babtie Group Ltd. 2002).

Harrison (2005) examined the impact on a potential low-head mini-hydro scheme on the River Teviot in the Scottish Borders, using a software suite simplified from Harrison & Whittington (2002). The use of the UKCIP02 scenarios for 2020 suggested that use of uniform annual changes in precipitation and temperature underestimates the extent of change, with substantially larger drops in summer flows than increases in winter flows. In production terms, the turbine capacity limit means that virtually no additional power is produced during the winter relative to current conditions. However, the significant drops in summer flows mean that the scheme is idle for more of the season and consequently summer production drops by over a fifth. The larger potential in winter means that annual production is impacted to a lesser degree although the drop is still appreciable.

A more recent study by Duncan (2014) applied the UKCP09 Weather Generator to sophisticated hydrological models of five representative catchments in Scotland. The range of flows bounded by the 10% and 90% probabilities for the weather generator-derived baseline (1961-1990) and the 2050s (2040-2069), are shown in Figure 5 for the River Ewe. Observed data was found to be in line with modelled baseline flow duration curves, giving confidence that the weather generator and hydrological model will produce plausible flow duration curves for future climate. There is an increase in magnitude of flows at the higher percentiles and a significant decrease in baseflows. This would be consistent with other findings that increased storm events will drive large storm response while greater evapotranspiration will reduce summer low flows. Capacity factors for a hypothetical 16MW hydro scheme were shown to drop with significant falls in the summer. Slightly higher capacity factors are seen in winter albeit constrained by the turbine rating and design flow.

2.2.3 Solar power

Solar power presently contributes a relatively small proportion of generated energy, but generous Feed-in-Tariffs have helped stimulate recent growth. Further increases are expected as solar technologies mature and costs reduce. Solar irradiance levels reaching the surface of the earth, and thus solar power output, are dependent on cloud cover (Crook et al. 2011), (Pan et al. 2004). Human activity can cause a change in atmospheric particles (aerosols) which increase (or decrease) the volume of cloud condensation nuclei.

The impact of climate change on solar energy has been explored to some degree. (Gueymard & Wilcox 2011) investigated the long term solar resource in the U.S. and highlighted the seasonal changes in the solar resource. (Pan et al. 2004) uses a regional climate change model with results suggesting that seasonal irradiance in the US may decrease by up to 20% by the end of the 2040s.

(Burnett, D. et al. 2014) characterises the UK solar resource to provide a detailed assessment of the baseline climate which is combined with UKCP09 probabilistic output to explore the effect of climate change. Future UK solar resources at a regional and local scale are estimated. The results show an overall increase in resource over the UK, especially in southern and south-westerly locations. However, there will be increased seasonal variability, most notably in southern regions. It is expected that present regional differences in solar resource will be further increased in the future with southerly regions benefiting from increased solar energy resource in summer, while the relatively poor northerly resources will decrease slightly. In winter most regions will witness increased cloud cover and slightly reduced solar energy resource.

2.2.4 Wave power

Wave energy converters (WECs) rely on waves formed by the interaction of the wind with the ocean surface. Waves observed at a location have a seemingly random appearance because they are, in fact, a large number of interacting harmonic waves of different amplitudes, periods, directions and phases (Holthuijsen 2007). These individual waves may be generated great distances away from the location of the observer - for example, the wave climate on the western coast of the UK is greatly influenced by waves generated in the middle and western regions of the North Atlantic.

A time-series of surface elevations (or waves) can be transformed into an energy variance spectrum from which parameters describing the sea state like significant wave height (H_s) and energy-averaged wave period (T_e) may be obtained. The power flux (in kW per metre of wave front) can be calculated from these as:

$$P = 0.49 H_s^2 T_e$$

The wave climate is likely to change as a direct consequence of changes in wind patterns. The increase in the roughness of waves in the North Atlantic has been discussed for over three decades (e.g. (Neu 1984; Carter & Draper 1988). Changes such as these would be expected to have some effect on electricity generation by WECs.

A study of the Wave Hub site in Cornwall (Reeve et al. 2011), using winds corresponding to the IPCC A1B (intermediate emissions) and B1 (low emissions) scenarios, indicated that there was likely to be a 3% increase in the mean available wave power for the A1B scenario along with a wider spread of incident wave heights but contrastingly, a 2% decrease for the B1 scenario. The authors found an overall decrease in power conversion in both scenarios, however, which was attributed to the fixed performance characteristics (often presented as a power matrix) of WECs, leaving them unable to convert the additional power available under the A1B scenario. The projected changes fall well with the uncertainty bounds associated with the input wind data, and should, therefore, be regarded as highly uncertain. Other studies linking the variability in wave climate to the North Atlantic Oscillation (NAO) have yielded similar results (Mackay et al. 2010).

2.2.5 Bioenergy

The likely effects of climate change on bioenergy could fall into two areas. Firstly, the typical power generation cycle used in several bioenergy approaches is, in theory, sensitive to ambient temperature, with warmer cooling water or air reducing efficiencies. A study (Förster & Lilliestam 2010) based on a hypothetical nuclear plant located in central Europe, but applicable to any river-cooled thermal plant, showed that concurrent increases in river temperature and decreases in river flow could impact quite significantly on power production. This would apply similarly to coastal thermal plant, with a predicted rise in sea water temperatures reducing their cooling efficiencies.

The second, and possibly more serious, consequence of climate change for biomass-fuelled generation is the impact on the growing cycle of biofuel crops. A report analysing maize production in the US suggests that an increase in the variation seen in temperature and precipitation would lead to subsequent variation in biofuel production (Hatfield & Singer 2011). Managing the uncertainty resulting from this is a key issue for the industry. (Bellarby et al. 2010) use a model to project changes in the suitability of different areas of the UK for growing different types of biofuel crops. The authors note that the model is fairly simple and the assumptions made create associated uncertainties, but indications are given that certain crops, such as willow, which are currently popular as biofuels in the UK, may become less suitable under future climate conditions. An additional factor to consider under changing climate is the migration of crop pests and pathogens (Bebber et al. 2013).

2.3 Changes in extreme climate

A major consideration for future climate change scenarios is the potential for increased frequency of extreme weather events, which could have major impacts on renewable generation infrastructure.

Sea-level rises are a widely predicted impact of climate change. Co-fired or biomass plant that is coastally located could be subject to inundation during high tides. Tidal generators, whilst not dependent on climate factors, are potentially vulnerable to resource changes linked to sea-level rises. The potential for changes to the tidal constituents due to sea-level rise is described in (Pickering et al. 2012), and does indicate that if a large degree of sea-level rise were to occur, changes in tidal characteristics around the UK would be expected.

In very high wind conditions, wind turbines will stop producing power and in order to prevent damage. More frequent and persistent storms would increase the amount of 'lost' energy due to this process. The fatigue loading on the blades and tower structure would also be increased. The survivability of any technology located in a marine environment is a critical consideration in project planning. It was found in (Reeve et al. 2011) there is likely to be an increase in the occurrence of extreme waves at the Wave Hub site for the future scenarios. This is in accordance with the findings of (Perrie et al. 2004), which showed that climate change is likely to slightly increase the wave heights generated in large storms.

Prolonged periods of precipitation onto saturated ground present a high flood risk to all assets and infrastructure, including renewable generation plant. For hydropower, extreme flooding can lead to the spillways exceeding their design limits, whilst run-of-river plant could suffer inundation. The opposite situation of more frequent extreme drought is also likely to affect river-cooled thermal plant and also, obviously, hydropower generation.

Extremes of low temperature present a potential risk to wind turbine blades, causing icing (Pryor & Barthelmie 2010), and freezing of rivers would likely reduce hydropower output during critical cold spells when demand is at a peak. High temperatures present most risk to thermal plant operation, affecting cooling water/air temperatures and reducing efficiencies.

3. Assessment and management of risks

3.1 Impact of changing mean on cost of energy

This section addresses the potential for climate change to affect the cost of energy. Where possible, the most sophisticated and up-to-date probabilistic climate modelling framework for the UK provided by the UK Climate Impacts Programme (UKCP09) has been used here, along with some varying assumptions for baseline climate. UKCP09 offers a number of different ways of accessing and analysing data for future climate change scenarios at different levels of detail (UKCP09 2012).

3.1.1 Wind energy

The wind speed data provided by UKCP09 is more limited than other variables, due to lower confidence in the models (Sexton & Murphy 2010). The range of changes in future surface wind speeds summarised in (Sexton & Murphy 2010) is relatively small and spans both positive and negative changes. Figure 6 shows some of the percentage changes in wind speeds in the 2050s found from the 11 runs of the HadRM3 ensemble at the 50% probability level for a 'medium' emissions scenario. To consider impacts on wind energy output, the wind speeds from UKCP09 have been used to derive baseline and future UK wind generation scenarios based on the locations of existing wind farms and their capacities. The future values of the levelised cost of energy (LCOE) from wind have then been derived using the method described in (DECC 2012). The LCOE represents the unit cost of electricity over the lifetime of the generating assets by discounting the capital expenditure, operational costs and annual energy production to net present values. A key input to the LCOE calculation is the expected resource, and thus the expected level of annual generation. By assuming fixed capital and operational costs in all scenarios, and varying the resource as projected by the climate models, the impact of changing resources on the LCOE can be ascertained. Given the uncertainty associated with the climate projections, these figures are intended as an indication of possible changes rather than definitive figures. It is important to highlight that this analysis is looking solely at energy production and does not account for climate impacts on operational environments – for example, increasing extreme winds causing higher maintenance requirements.

Table 1 shows the change in LCOE for groups of onshore capacity, and offshore capacity from the Crown Estate Leasing Rounds 2 and 3. The baseline climate was created from the 1960-1990 daily averages from the HadRM3 model. The direction of changes is highly uncertain, typically positive at the 10% probability level and negative at the 90% level. The magnitude of the changes is relatively small at the 50% probability level, but the more extreme changes are more significant. The geographic spread of changes is such that the current northern bias is further enhanced, with some slight decreases in LCOE in the future, whilst the south east of England sees some future increases in LCOE as the wind output reduces.

Table 1 Climate change impact on UK wind energy LCOE – change in £/MWh

		Emission Scenario - 2050								
	Baseline Climate	Low			Medium			High		
		10%	**50%**	90%	10%	**50%**	90%	10%	**50%**	90%
Onshore Wind	84.31	5.24	**0.71**	-3.14	5.24	**0.71**	-2.93	5.51	**0.47**	-3.36
Offshore R2	115.69	9.64	**2.19**	-3.56	10.37	**2.5**	-3.56	10.37	**2.19**	-3.85
Offshore R3	117.30	6.51	**1.19**	-2.87	7.17	**1.49**	-2.87	7.17	**1.19**	-3.15
All Offshore	116.62	7.83	**1.61**	-3.17	8.52	**1.92**	-3.17	8.52	**1.61**	-3.45
All Wind	114.69	7.67	**1.55**	-3.19	8.31	**1.83**	-3.17	8.33	**1.53**	-3.47

3.1.2 Solar, hydro and wave energy

In a similar manner to the previous results presented for wind, levelised costs were calculated for solar, hydro and wave power using a method leveraged from (MacDonald 2010) and described in full in (Burnett 2012). Baseline economic parameters are derived from a number of sources: wave – (Allan et al. 2011); solar – (International Energy Agency 2010); and hydro – (MacDonald 2010), all representative of the observed climate from 1960-1990. Future climate change is applied using a range of UKCP09 outputs: hydro – weather generator; solar – probabilistic framework; wave – HadRM3 wind speeds combined with the methodology described in (Harrison & Wallace 2005) to derive wave height and period. As with the analysis of the LCOE for wind energy, all other inputs to the calculation are kept constant across all scenarios. The results are shown in Table 3. It should be highlighted that the baseline numbers are calculated using more tentative assessments of capacity factor than the wind figures from Table 1, and cover only a single emissions scenario.

Table 2 Climate change impact on UK solar, wave and hydro energy LCOE – £/MWh

		Emission Scenario - 2050								
	Baseline Climate	Low			Medium			High		
		10%	**50%**	90%	10%	**50%**	90%	10%	**50%**	90%
Hydro	**83.2**				97.9	**87.6**	77.4			
Wave	**193.0**				211.5	**198.4**	187.8			
Solar	**237.7**				239.2	**230.8**	222.4			

3.2 Adaptation

Adaptation to climate change can take many forms, depending on the severity and nature of the changes that occur. (Mukheibir 2013) categorises types of adaptation into a range of different responses, indicating factors including the timeframe, coverage and drivers of different adaptations.

The highest likelihood scenarios appear to feature only small changes in wind energy output, so short-term adaptation measures would thus appear to be unnecessary, and investment risk related to climate change would seem to be low. Existing spatial patterns persist, and reconfiguration of capacity locations would likely be unnecessary. The potential for long-term adaptation to increasingly frequent high wind speeds could be built in to machine design – for example, rather than shutting down completely in high winds, the blades gradually turn away from the prevailing wind and reduce output (Enercon 2014). Similarly, many WECs are 'tuned' to produce their maximum output in the most frequent types of sea-state occurring where they are located, and could be re-tuned to adjust to different prevailing conditions (Reeve et al. 2011).

Alteration of hydropower reservoir operating rules is likely to be necessary in a changing climate ((Weyman & Bruneau 1991; Minville et al. 2010)). More major site-specific adaptations may be necessary, for instance raising dam walls and enhancing spillway capacity to cope with additional flood waters, or uprating turbine capacity (Harrison 2005; Duncan 2014). For bioenergy, it may become necessary to change the type of crop used in order to obtain maximum yield under different temperature and precipitation conditions.

The already significant variability in renewable output requires careful management by the network operators to ensure demand is met. An increase in the short-term variability of renewable output could lead to more extreme 'good' and 'bad' years, which could also have an effect on perceived investment risks. This may be a particular issue for small scale or community developments with only a single plant in their portfolio and limited scope to diversify. In the case of an increase in variability, it would seem sensible to invest in two areas – improved short and medium-term weather forecasting, and efficient and cost-effective storage facilities. Forecasting of wind speeds is generally good in the very short term, but can be very difficult over time periods greater than 2-3 days. Many storage technologies are in development and may prove suitable to provide a (partial) ‘buffer’ to reduce the dependence on responsive fossil-fuel plant as back-up generation. ‘Virtual power plants’ and demand management may also provide similar facilities.

The close coupling of all types of renewable energy and demand to weather patterns means that the impacts of climate change on each factor cannot be considered in isolation. For example, increasing ambient temperatures in summer could result in a greater requirement for space-cooling which, when combined with a reduced mean wind resource, would require alternative generation. Solar power may be more suitable for providing this energy, but the concurrent generation and demand patterns would need to be studied to ascertain the precise gap and the ability of solar to fill it. Such changes imply changes to overall capacity credits from renewable technologies and analysis of combined supply and demand on an aggregate basis would seem sensible.

4. Discussion

4.1 Confidence in the science

In general, confidence in the output of climate models among qualified scientists is very high, but a clear understanding of the uncertainties and sensitivities is needed. On temperature, there is agreement between models and a significant association between carbon dioxide emission levels and trends in temperature change. The same level of confidence does not exist with respect to other weather variables. In particular, surface-level wind speed is difficult to model on a scale applicable to wind power generation. As discussed in previous sections, different models give different results, and the direction of projected change is inconsistent. As computing power increases, and consequently the resolution of models improves, higher confidence may be achieved.

The current generation of modelling is, however, still valuable in providing a framework against which to test the resilience of renewable energy systems to climate change. Table 3 summarises the potential impacts and the existing levels of confidence in the modelling of these impacts. Considering the model outputs as possible future scenarios rather than a deterministic future prediction allows testing of various aspects of the system against a range of plausible future conditions.

Table 3 Summary of confidence

Specific impact	Volume of evidence	Agreement	Impact	Comments
Small changes in mean annual wind power output	Medium	Medium	Low	The range of changes suggested by many of the models are relatively low and will thus have a small impact

Decrease in summer hydropower production	Medium	Medium	Low-Med	Still a range of uncertainties in the modelling but there could be some reduction in summer production
Increase in winter hydropower production	Medium	Medium	Low-Med	Dependent on ability of scheme to utilise extra flow, but could be some increase in production
Enhancement of existing north-south solar production differences	Low	None	Low	Single study, scale of changes very minor
Small changes in mean annual wave energy production	Low	None	Low	Wave energy currently contributes only a small amount to the energy system, so impacts of changes in output are minimal
Sea level rise leading to changes in tidal energy production	Low	None	Unknown	Not currently quantified, but some evidence that sea-level rise could change tidal flow patterns
Reduced wind power due to extreme high winds (turbines stop producing)	Low	None	Low	Small risk of occurrence within the ranges currently predicted
Increased failure of wind turbines due to extreme high winds	Med	Low	Med	Some evidence but specific impacts are difficult to ascertain
Increased failure of wind turbines due to blade icing in extremely low temperatures	Med	Med	Low	The occurrence of such events is likely to remain very low
Reduced access to offshore wind turbines (and wave/tidal energy devices) due to increased storms	Low	None	Low	It is likely that adaptations to maintenance strategies will be possible in the event of reduced access

4.2 Research gaps and priorities

Obviously, given the lack of confidence in the projections of future wind speeds, and the clear intention to increase the use of wind power generation in future, research on the physics, dynamics and modelling of wind conditions is critical. Increasing understanding will also drive improvements in forecasting, which is imperative to assist with managing variability. Wind models provide direct input to wave models, and thus improvements in the skill of wind modelling will also have a positive impact on the success of wave models. These are important not only for analysing wave energy generation potential, but also loading conditions, reliability and accessibility parameters for other offshore renewables.

It is necessary to focus research on designing adaptable and resilient machines for future conditions. The provision of increasingly reliable estimates for design and resource parameters will allow machine designers to factor in climate change, but the range of uncertainties must be clearly communicated.

The cost of climate change and the associated level of risk is currently only able to be estimated. Combining the many levels of uncertainty within the climate data, the engineering models and the economics is a complex task which has not been sufficiently addressed as yet.

6. Conclusions

The impact of climate change on renewable energy generation is a developing area of study for the engineering community. Understanding the potential for different future climates to change the magnitude and pattern of available energy is particularly important as investment in renewables grows, and the technologies form a more substantial part of the electricity system. The current generation of models discussed here show some impacts, generally in the low-medium range of severity. The confidence in the models, however, is quite low, and a number of specific areas of uncertainty have been highlighted that require further research and analysis.

Some of the key issues that have been identified are: that increased extreme wind events would potentially have a medium degree of impact, causing more wind turbine failures, but despite a reasonable volume of evidence the agreement regarding specific outcomes is low; sea-level rise could have an effect on tidal energy generation but, as yet, the lack of specific analysis means the impact is entirely unknown; there is a medium level of agreement surrounding projected hydropower changes, but the impact of the changes is in the low-medium category.

There is a conceivable investment risk associated to climate change, and thus the development of robust technology and processes to manage and adapt to future scenarios is imperative. Using different future climate scenarios in an analysis of LCOE for different technologies indicates relatively small potential changes due to modelled changes in energy production, which are likely to be less significant than other uncertain factors affecting the cost of energy. The cost of more subtle changes, such as an increased frequency of extreme events, requires further evaluation.

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Figure and table captions (images as individual files separate to your MS Word text file).

Figure 1 Relative contribution of different renewable technologies

Figure 2 Operational wind farms (October 2013)

Figure 3 Typical wind speed distributions

Figure 4 Example flow duration curve and energy generation for current and future climate

Figure 5 Flow duration curves for River Ewe for baseline and 2050s climate (after Duncan, 2014)

Figure 6 Wind speed change (%) for 2050s medium emissions scenario with 50% probability

Table 4 Climate change impact on UK wind energy LCOE – change in £/MWh

Table 5 Climate change impact on UK solar, wave and hydro energy LCOE – £/MWh

Table 6 Summary of confidence